FEASIBILITY STUDY OF ALTERNATIVE NON-GEOSTATIONARY SATELLITE CONSTELLATIONS FOR COMMUNICATION

by

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DEPARTMENT OF AEROSPACE ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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FEASIBILITY STUDY OF ALTERNATIVE NON-GEOSTATIONARY SATELLITE CONSTELLATIONS FOR COMMUNICATION

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Sqn Ldr D Chakravorty

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CERTIFICATE

It is certified that the work contained in the thesis entitled "**Feasibility Study of Alternative Non-Geostationary Satellite Constellations for Communication** ", by **Sqn Ldr D Chakravorty** has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

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Abstract

In view of the explosive growth of demand for present and projected communications, satellite communication has become of vital importance. The geostationary satellites easily appear as the first choice, especially for coverage over non-polar regions. This evidently follows from the ease and convenience facilitated by the use of "non-tracking" and highly directional antennas possible for communication between users through the apparently fixed satellite system. However, the geostationary arc being a limited resource, efforts are on to look at suitable alternatives which may have to be called upon for supplementary communications capacity if predictions of saturation of spacecraft occupancy of the geostationary ring come true.

In this study an attempt has been made to study the feasibility of using various possible non-geostationary satellite constellations as an alternative to the geostationary satellites and assess their relative merits and demerits. The consideration of non symmetric satellite constellations in polar orbits, symmetric inclined satellite orbit constellations as well as quasi-stationary orbits have been taken up as the possible alternatives to the GSO. The various problems associated with using these systems are also discussed.

The non-symmetric polar orbit satellite constellation and/or the symmetric inclined rosette constellations appear to be the likely choices for augmenting the available satellite communications capacity in the foreseeable future. The polar configuration may be preferred for Australia, Alaska and the European countries with special interests in near polar coverage over their near polar latitudes.

It is felt that circular, non-equatorial, 24-hour orbits may represent a truely unexplored "gold-mine" for satellite communications. It appears that the predominant relative apparent north-south drift faced by satellites with respect to the ground users poses a major technological problem at present. Efforts already on for achieving fixed relative orientation with respect to moving ground station through variable satellite attitude control are likely to overcome this major hurdle in not too distant a future.

Acknowledgement

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D Chakravorty

List of Symbols

E	eccentric anomaly
e	eccentricity
h	height of orbit
i	orbit inclination
i,j,k	unit vectors in the directions of x, y, z axes respectively
M	mean anamoly
m	harmonic factor of rosette constellation
n	ratio of final orbit radius to parking orbit radius
p	number of orbit planes in a constellation
q	number of satellites per orbit
r	satellite orbit radius
$\mathbf{r}$	vector notation for satellite orbit radius
R_E	radius of Earth
$\mathbf{R_E}$	vector notation for radius of Earth
r_p	parking orbit radius
T	time period of satellite orbit
t	time
u	angular position of satellite w.r.t. nodal line in ascending direction

Γ	inter orbit angular separation
λ	longitude
μ	Earth's gravitational constant
ν	true anomaly
σ	satellite elevation angle
σ_m	minimum guaranteed satellite elevation angle
ϕ	latitude
χ	time variable phase angle of satellite
ψ	great circle range
Ω	right ascension of ascending node
ω	arguement of perigee
ω_e	angular rotation rate of Earth
$\Delta \bar{V}$	dimensionless velocity increment
Δi	change in inclination

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Chapter 1

Introduction

In October, 1945 Arther C. Clarke published a paper in "Wireless World" that proposed a worldwide system of communication using three satellites orbiting the Earth in a geostationary orbit. That may be viewed as a first landmark in the history of satellite communication. This vision took another 12 years to come to fruition when the erstwhile USSR developed the technology that allowed the SPUTNIK satellite to be launched. It took another five years before satellites were put to use for communications applications.

The first communication satellites were put into elliptical orbits that resulted in an orbit time less than three hours; an example being Telstar which orbited the Earth in 157 minutes. These satellites required special earth station design to allow the satellite to be tracked while it was in the earth station's window of view. They, however, required low transmitting powers and receiver sensitivities. In contrast, the geostationary satellites present no tracking problems but are so far away that large antennas , high powers and high receiver sensitivities are essential. whether to use a stationary satellite or a succession of satellites in lower orbits for global communication was a question that exercised the minds of communications engineers in the early 1960s. It was really a case of convenience versus distance, and distance won. The first geostationary satellites, such as the SYNCOM, were launched in 1963, to relay television from the 1964 Olympic Games.

In view of the explosive growth of present and projected communications requirement satellite communication has become of vital importance. Special attention has been paid to orbit and frequency spectrum utilization. This need arises out of the fact that the geostationary arc is a finite resource which limits the number of satellites that can be

in orbit at any one time. Particular attention has been paid to satellite station-keeping, frequencies being used by adjacent satellites and the satellite's transmission and reception characteristics.

The capacity of the geostationary arc being limited, efforts are on to look at suitable alternatives. For the first time since the beginning of the satellite communications era, non-geostationary satellites are being considered for commercial communications. This represents a reverse trend in the evolution of satellite technology. Some of the alternatives are already at the stage of advanced investigation and development. However, the situation is very fluid, costs involved are high and the need for an economic and feasible satellite system for communication poses formidable challenges on various fronts. This calls for detailed analysis of existing satellite orbits in use along with other alternate possibilities which have received relatively less attention. Here, we propose to look at the feasibility of some of the newer and feasible alternatives to the geostationary orbit (GSO), especially the low-earth orbits (LEO), intermediate circular orbits (ICO) and the quasi-stationary orbits (QSO). For completeness, these orbits are described below [1,7]

(a) Intermediate circular orbits (ICO): These are circular inclined orbits at altitudes of about 10,000 km – using the available free space between the two radiation belts – offering a global coverage with constellations of typically 10-15 satellites. As a result of their relatively high altitude, the satellites are moving slowly with respect to the users, and remain in visibility, during each pass, for periods of time $\sim$1-2 hours. The elevation angle is typically larger than 40^o for half the time. The propagation delay is typically $75 - 100$ ms compared to about 250 ms associated with the GSO. The ICO falls under the more general category of medium earth orbits (MEO) having an altitude range of 5,000 to 20,000 km. Examples of ICO systems are TRW's ODESSEY (American) and ESA's MAGSS-14 (European).

(b) Low Earth Orbits (LEO): These are circular orbits , below the radiation belts, at altitudes $\sim$ 500-2,000 km and yet high enough to avoid atmospheric drag. Constellations entail several tens of satellites (20–70), the numbers increasing with decreasing altitude and increasing minimum elevation angle. Propagation delay is of the order of 5–35 ms. Satellites are visible for a short period of time, typically 10 minutes, and that necessarily involves frequent handovers from "setting" satellite to "rising" satellite, even more so for beam-to-beam transfer as required fo

the satellites equipped with multibeam antennas. The rapid relative motion of the satellite implies a Doppler shift of typically 0.002 percent of the carrier frequency (30 KHz at L-band). Examples of these constellations are IRIDIUM (Motorola), GLOBALSTAR (Loral) and CALLING (Calling Comm. Inc.).

(c) Highly Elliptical Orbits (HEO): these are elliptical inclined orbits, with inclination equal to 63.4^o to ensure the orbit stability. They offer enhanced duration of coverage (4–8 hours) of the region located under the apogee. With proper phasing and orbit parameter selection, three to six satellites can provide multiregional coverage, for instance, North America, Europe and East Asia with a typical minimum elevation angle of 40^o. As a result of apogee altitudes (25,000–45,000) where the satellites are mostly in use, the propagation delay is not necessarily smaller than that with geostationary systems. Moreover, satellites orbit through the radiation belts twice each orbit, and this has implications on the lifetime of the satellites. However, the biggest advantage of these satellites is that they can provide zonal coverage at polar regions. Examples are MOLNIYA, ESA's ARCHIMEDES experimental satellite and, in lower orbits, ELLIPSO.

(d) Quasi-Stationary Orbits: Deployments which cause the subsatellite point of a satellite to follow fixed ground track patterns on the Earth's surface are referred to as "quasi-stationary" [7]. They are obtained by choosing integer ratios between the orbit period of the satellite and the Earth's rotation period, like 24-hr and 12-hr inclined orbits and are not bound by a region of altitudes. The motion of the satellites over a fixed ground track on the Earth's surface leads to practical simplifications in the realm of antenna beam-steering design. Examples are NAVSTAR GPS or GLONASS satellites in $\sim$ 12-hr orbits.

The advent of LEO satellites has made personal communication possible even from the most remote regions where geostationary satellites may have no access. Due to the low communication powers involved, the user can directly contact the satellite without any separate earth station. The time delay involved is also comparatively less. The disadvantage is the requirement for a larger number of satellites with a more complex tracking system. However, the satellites can be smaller and less complex.

In this study an attempt has been made to develop a complete perspective concerning

the feasibility of using the non-geostationary satellite constellations for communications. Chapter 2 gives an overview of the various considerations governing the selection of an orbit for communication satellites. Chapter 3 presents a detailed analysis of certain specific types of non-geostationary orbit (NGSO) constellations which may be used to provide continuous global coverage. The focus is on quasi-stationary orbits for global as well as zonal coverage so as to supplement the geostationary satellites. The problems of intersatellite interference, frequent handovers, tracking, etc. due to the use of multiple number of NGSO satellites are discussed in the next chapter. Finally, the conclusions and recommendations for future work are presented in the last chapter.

Chapter 2

Factors Affecting Selection Of a Communication Satellite System

The various aspects of a satellite motion likely to affect the applicability of its orbit for communication are as follows.

- Visibility of a satellite from ground station.
- Communication power requirements.
- Satellite attitude and position drift control and tracking requirements.
- Launching power requirements.
- Disposal options for satellites after their useful life.
- Radiation hazards in space.

2.1 Visibility of Satellite from the Ground Station

An important condition affecting the tracking requirements for satellites and their use as an instantaneous communication relay is its visibility from the ground stations being used for this purpose. This in turn is directly dependent on geometry of satellite motion relative to the ground station. So, we initiate our study by analyzing this geometry.

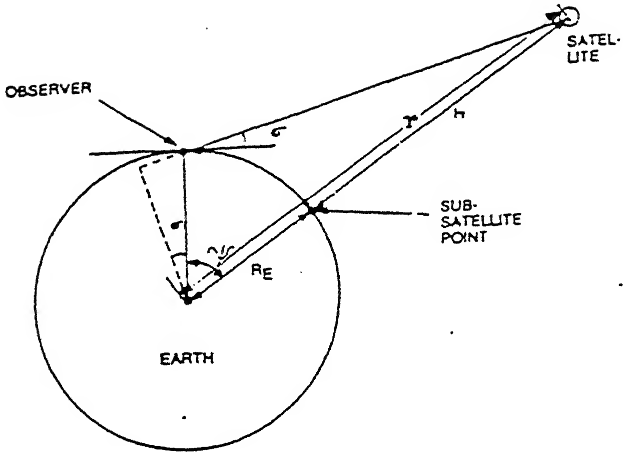

Figure 2.1: Geometry of satellite motion [5]

2.1.1 Geometry of Satellite Motion

We consider a satellite moving in an orbit around the Earth with its centre at O (Fig. 2.1). The point B represents the subsatellite point. The line joining the satellite with ground station G defines the instantaneous line -of-sight. The angle σ defines its elevation. This angle directly influences the angle ψ, called the great circle range. It is easy to see that the visibility of satellite from the ground station is assured provided the following inequality is satisfied [8,9].

$$\cos\psi > \frac{R_E}{r} \tag{2.1}$$

where,

$$\cos\psi = \frac{\mathbf{R_E}\cdot\mathbf{r}}{|R_E||r|} \tag{2.2}$$

Here. Eqn. 2.1 corresponds to the grazing elevation angle and does not consider the effect of atmosphere on radiations. In practise, these effects impose additional constraints on minimum σ so as to ensure the satellite visibility from the ground station. Evidently, higher is the altitude of orbits, longer would be the relative periods of visibility. Position

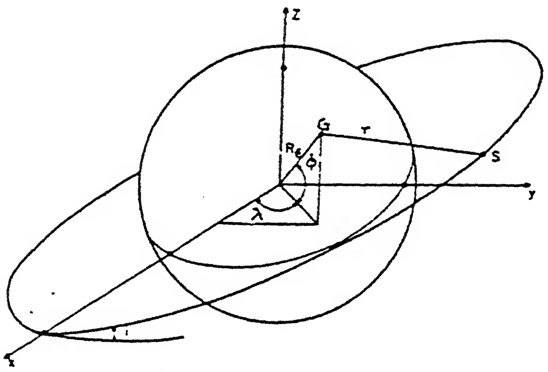

Figure 2.2: Earth station geometry [11].

vector of the ground station G (Fig. 2.2) can be given in equatorial coordinates as

$$\mathbf{R_E} = R_E \cos\phi \cos\lambda\, \mathbf{i} + R_E \cos\phi \sin\lambda\, \mathbf{j} + R_E \sin\phi\, \mathbf{k} \tag{2.3}$$

where.

$$\lambda = \lambda_o + \omega_e t \tag{2.4}$$

The radius vector of the satellite can be found in terms of its orbital elements (Fig. 2.3).

$$\mathbf{R} = R_x \mathbf{i} + R_y \mathbf{j} + R_z \mathbf{k} \tag{2.5}$$

where.

$$\begin{aligned} R_x &= R(\cos u \cos\Omega - \sin u \cos i \sin\Omega) \\ R_y &= R(\cos u \sin\Omega + \sin u \cos i \cos\Omega) \\ R_z &= R \sin u \sin i \end{aligned} \tag{2.6}$$

where. $u = \omega + \nu$. Using Eqns.2.2. 2.3 and 2.6 we can show that

$$\cos\psi = \cos\phi\,[\cos u \cos(\lambda - \Omega) + \tag{2.7}$$

$$\sin u \sin(\lambda - \Omega) \cos i] + \sin u \sin i \sin\phi \tag{2.8}$$

Thus. given a specific orbit and time t. we can find the angular distance of the satellite from the ground station.

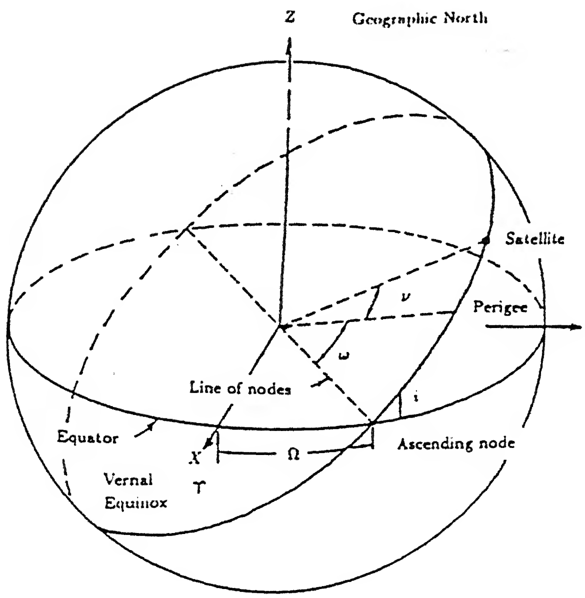

Figure 2.3: Orientation of an earth station [5].

2.1.2 Minimum possible elevation angle

As indicated above, reliable line-of-sight with any spacecraft is achieved only above some minimum elevation angle. When the spacecraft is well above the horizon, the effects of atmospheric noise contributions ,fading and frequency dependent attenuation are minimized. An elevation angle of at least 5^0above the horizon is recommended in any system design, however, an angle of 10^0 is preferable with a view to minimize the Earth's contribution to the equivalent noise temperature of the receiving system and hence greater reliability. At elevation angles less than 5^0 the tropospheric portion of the propagation path is so long that turbulence may cause rapid amplitude and phase modulation or variation called SCINTILLATIONS [10]. In addition, the waves may arrive simultaneously at a receiving antenna via several propagation paths and, by interfering with each other, may give rise to multipath fading, also called frequency - selective fading. Since, the global coverage is intended, for the purpose of this study, only circular orbits have been considered. The necessary and sufficient geometric condition for line-of-sight communition between the satellite and the ground station can be explained through Fig. 2.4. For visibility, the satellite must lie on the spherical cap within cone of semi-vertex angle of $90^o - \sigma_m$, with its apex at the ground station G. Here, σ_m is the minimum elevation angle

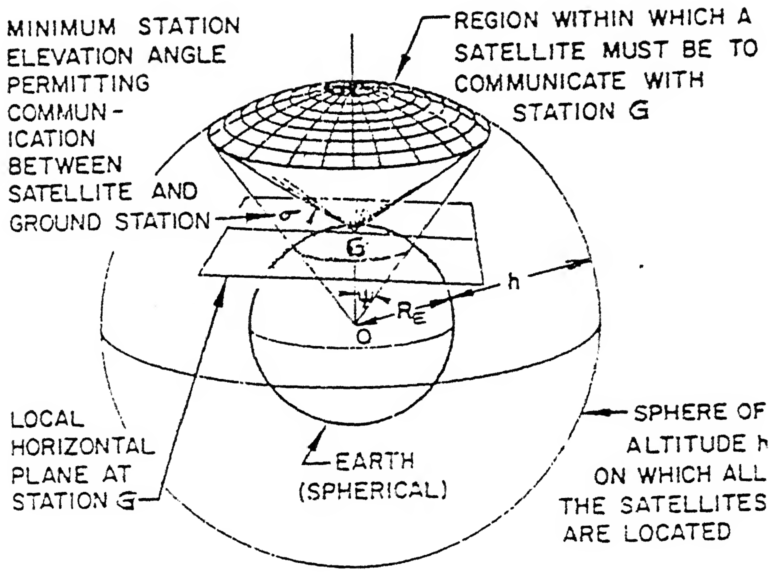

Figure 2.4: Geometry of mutual visibility [12]

that permits a signal to be transmitted to or received from a satellite by a ground station. Needless to say, the satellites in circular orbits at the same altitudes(h) even though in different planes must lie on the shaded spherical cap for line-of-sight communication. We, therefore, refer this region to as communication region (CR). The communication region for the station G is now given by the radial projection of the shaded cap onto the surface of the Earth. These satellites can communicate with the station G if and only if its sub-satellite point falls within CR. Through consideration of geometry, we can show that the great circle range ψ of the CR is related to the altitude h of the orbit and σ_m as follows [12].

$$\psi = \left[\cos^{-1}\left(\frac{R_E \cos\sigma_m}{h + R_E}\right) - \sigma_m\right] \tag{2.9}$$

Thus, given the angular distance ψ of the satellite from the ground station at any instance the elevation angle can be found from

$$\tan\sigma = \frac{\cos\psi - \frac{R_E}{r}}{\sin\psi} \tag{2.10}$$

The satellite will therefore be visible to a ground station if $\sigma > \sigma_m$.

Table 2.1: Comparison of transmitted power at various altitudes

S.No	orbital period T(Hrs)	orbital height h (km)	power as %age of power in GSO	reduction in power (dBW)
1	1.5	275	0.006	42.29
2	3	4183	1.37	18 65
3	6	10386	8.42	10.75
4	8	13930	15.15	8.19
5	12	20223	31.96	4.95

2.2 Communication Power Requirements

A fundamental determinant in any system design is the distance over which communication must be maintained. The equation for free space transmission loss (actually a function of dispersion rather than attenuation) between ideal loss free isotropic (unity gain) antennas is

$$L_p = \left(\frac{4\pi R}{\lambda}\right)^2 \tag{2.11}$$

where.

$$\begin{aligned} L_p &= \text{free space loss (numeric)} \\ R &= \text{transmission range} \\ \lambda &= \text{wavelength of propagation.} \end{aligned}$$

Expressed in decibels and in terms of frequency in megacycles Eqn.2.11 becomes

$$L_p(dB) = 32.5 + 20 \log f\,(MHz) + 20 \log R\,(km) \tag{2.12}$$

From these equations it is clear that keeping everything else constant. the transmitted power has to be increased as square of the distance to overcome the free space losses. Therefore. as the orbital height decreases the transmitted power also decreases. Table 2.1 shows the amount of reduction in transmitted power from GSO to different orbital altitudes. This is a clear indication of the substantial reduction in transmitted power with decreasing altitudes (it may be noted that a 3 dB reduction corresponds to half power).

In practice, however, different systems use different types of antennas which suit their own requirements and hence transmitted power has a higher value than that shown in Table 2.1. Some examples are as follows:

(a) The transmitter antenna beamwidth required to give the same amount of coverage increases as altitude decreases. Thus, a higher transmitter power is required to give the necessary flux density at the Earth station antenna.

(b) The antenna used in mobile user link (MUL) terminals for the LEO systems are usually low gain omnidirectional antennas. Thus, a higher flux density is required to give the necessary input power to the receiver. This calls for higher transmitted power.

However, the low transmitted power is quite clearly evident in the MUL terminals of LEO systems where the terminal power is of the order of only 0.5 to 1 watt.

2.3 Satellite Attitude and Position Drift Control and Tracking Requirements

For communication satellites, it is necessary to maintain the satellite at a fixed orientation with respect to the earth station. The non-geostationary satellites are continuously moving with respect to the Earth station. Hence, the tracking system becomes more complex for these systems. There are various attitude control methods as listed below but each has its advantages and limitations in terms of mass penalty, hardware complexity and precision of control.

(a) Passive control

- Spin stabilisation
- Gravity gradient stabilisation

(b) Active control

- Rocket thrusters
- Momentum wheels

- Reaction wheels

The tracking requirements for different systems vary depending on altitude and the satellite mission objectives. In the LEO constellations, proposed to be used mainly for mobile communication, the station keeping requirements are not as stringent as the GSO satellites. Here, we have a large number of satellites used sequentially for providing global coverage and it is ensured that at least one satellite is always visible to the user. Moreover, the MULs use omnidirectional antennas through which any satellite within the visibility cone can be contacted. However, the hub stations used mainly for traffic routing and satellite control commands have to have a tracking strategy to select a particular satellite out of a number of visible satellites. Morever, there will be frequent hand-over from one satellite to another as the hub station passes from one cell to the adjacent one. Therefore, the hubstation must have a higher number of tracking antennas which adds to the hardware complexity and cost. In the case of inclined 24-hour quasi-stationary orbits the satellites suffer a periodic angular drift with respect to the ground station. The non-stationary nature of the satellites results in periodic oscillation of the line-of-sight with respect to the local vertical. Since these satellites define a fixed ground track during the orbital period, suitable control methods can be used for achieving a properly synchronized variation in the orientation of the satellite and ground based antenna.

2.4 Launching Booster Requirements

The energy requirement for launching a satellite increases with orbital radius. Hence, the launching cost of a GSS is much greater than that for an MEO or LEO satellite. Since the injection of a satellite into the final orbit is in general preceded by establishing a circular parking orbit first, the difference in boost energy for different orbits can be estimated from the difference in velocity increment required in transfer of the satellite from the parking orbit to the final desired orbit. Another factor which affects the boost energy is the impulse required for change of inclination from the parking to the final orbit. Since the minimum inclination possible for a parking orbit is equal to the latitude of the launch station, a change in inclination would be required if the latitude is different from the inclination. For higher inclinations (i.e. for $i > \phi$) a correct direction of launch is sufficient to provide the necessary inclination. However, if $i < \phi$ a higher impulse would

be required at the apogee of the transfer orbit to change over to the final circular orbit along with the necessary change in inclination. In the present analysis, the most common 2-impulse, minimum energy i.e. the Hohmann transfer trajectory has been considered for the transfer from the parking to the final orbit. Assuming a common parking orbit of radius r_p, the dimensionless expression for the total velocity increment required in transfer from the parking to the final circular orbit can be given by

$$\begin{aligned}\Delta\tilde{V} &= \left(\sqrt{\frac{2n}{1+n}} - 1\right) \\ &+ \frac{1}{\sqrt{n}}\left[\left(1 - \sqrt{\frac{2}{1+n}}\right)^2 + \sqrt{\frac{2}{1+n}}\left(2\sin\frac{\Delta i}{2}\right)^2\right]^{\frac{1}{2}}\end{aligned} \tag{2.13}$$

where,

$$\begin{aligned}\Delta i &= \text{change in inclination} \\ n &= \frac{r}{r_p} \\ \Delta\tilde{V} &= \frac{\Delta V}{\sqrt{\mu/r_p}}\end{aligned}$$

Table 2.2 shows the values of velocity increment for different values of n (which increases with the value of the final orbit radius) and Δi. For a 7.000 km radius parking orbit n=6 nearly corresponds to the GSO. This gives a clear indication of the extra impulse required for changing the inclination and the orbital altitude from the parking orbit.

2.5 Requirements for Disposal of Dead Satellites

Orbital debris can be defined as any man-made Earth orbiting object which is non-functional with no reasonable expectation of assuming or resuming its intended function for which it is or can be expected to be authorized. Orbital debris includes non-operational spacecraft, spent rocket bodies, materials released during planned space operations, and fragments generated due to explosions and collisions. This derelict hardware is strewn across a wide range of altitudes, but is clustered around regions where space activity has been the greatest, i.e. around LEO and GEO. Orbital debris may present a variety of

Table 2.2: Impulse requirement in terms of velocity increment

Δi^o	$n = r/r_p$					
	1	2	3	4	5	6
0	0.000	0.285	0.394	0.449	0.480	0.499
5	0.087	0.296	0.399	0.452	0.482	0.501
10	0.174	0.326	0.414	0.461	0.489	0.506
15	0.261	0.366	0.436	0.476	0.499	0.515
20	0.347	0.412	0.464	0.495	0.514	0.526
25	0.433	0.460	0.495	0.517	0.531	0.539
30	0.518	0.510	0.528	0.541	0.549	0.554

problems to the spacefaring community, from the possibility of catastrophic collision hazard to the corruption of astronomical observations and intermittent interruption of RF paths [13]. Once the operational lifetime of a satellite is over, i.e. it is no more functional it should be removed from the usable orbit region to prevent it from colliding with future functional systems. Due to the effect of Earth's gravitational field, it is most economical to deorbit into the Earth's orbit below 25,000 km altitude and to boost to higher orbit above that altitude.

2.5.1 The geostationary orbit and end-of-life disposal

In order to eliminate the risk of controlled spacecraft colliding with an abandoned spacecraft, geostationary satellites should be reorbited to a disposal orbit at end-of-life. Reorbiting into a disposal orbit should be established with a series of at least three burns in order to preclude deposit in a less desirable orbit due to unanticipated fuel depletion. The velocity requirement for reorbiting is 3.63 m/s or equivalent to about a month's station-keeping budget for every 100 km altitude increase [13].

Table 2.3: Lifetime of circular orbits [13].

Orbit Altitude (km)	Lifetime
200	1–4 days
600	25–30 years
1,000	2,000 years
2,000	20,000 years

2.5.2 Disposal of LEO/ICO satellites

The Earth's atmosphere produces drag forces that retard an orbiting object's motion and cause it to spiral into denser regions of the atmosphere where it typically burns up due to air friction effects. The less massive the object for a given c.s area. the greater its drag will be. resulting in a shorter lifetime in orbit. At higher altitudes (>1000 km) the atmospheric drag effects are virtually negligible(Table 2.3).

The LEO/ICO satellites. at the end of their operational life. can be deorbited by using propulsive maneuvers to ensure entry over oceanic areas so that can completely burnup and any remaining unburnt debris can fall into safer regions. The other methods of removal of LEO satellites can be

(a) drag augmentation by use of inflatable devices that would rigidize upon deployment. presenting a much greater cross-sectional area to the atmosphere to increase the drag force on the satellite. This works better for altitudes below 600 - 700 km.

(b) deployment of solar sails. which would use solar radiation pressure to change its orbital elements. Drag on these sails will also assist in the removal process.

(c) use of tether may also assist object removal process by momentum exchange at either deployment or retrieval and electromagnetic drag.

All these methods require development of complex hardware which will cause mass and performance penalties.

2.6 Radiation Hazards in Space

An environmental factor with strong influence on spaceborne electronics is the corpuscular radiation present in space. This radiation, largely consisting of charged atomic particles, interacts with matter and can sigficantly change the electrical properties of components in the communication system. The Van Allen belts (Fig. 2.5) play a major role in the selection of orbits for communication satellites. The Van Allen belts are zones of charged particles which are trapped in the Earth's geomagnetic field. The path of the particles is deflected by the magnetic fields and this prevents the particles from escaping the Earth's vicinity. Basically, the Van Allen belts consist of an inner zone of high energy (MeV) protons and an outer zone of high energy (keV) electrons in large quantities with both protons and electrons existing throughout the belt. These belts occupy a distorted torroid about the Earth, lying in the plane of geomagnetic equator. The energy and spatial distribution both undergo both regular and irregular variations with time. The inner belt extends from an altitude of about 1,300 km to 9,000 km, with the peak intensity at about 3,600 km above the geomagnetic equator. In latitude, the inner belt extends from 45°N to about 45°S magnetic latitude. The outer belt consists of electrons and protons with energies between 0.1 and 5 MeV. It extends from 9,000 km to about 60,000 km altitude, with central region of peak particle intensity at 16,000 km. The particle energy in the outer belt is less than that in the inner belt but particle densities are higher. Table 2.4 gives a summary of particle intensities at the geomagnetic equator.

2.6.1 Radiation damage on materials

The damage incurred by the electronic components, particularly the silicon solar cells, due to charged particle radiation encountered in the Van Allen belts pose a severe limitation to the life of the satellite. A "ball-park" view of the radiation susceptibilities of various materials and components is presented in Table 2.5. It is seen that the damage thresholds for electronic components are much lower than that for other types of materials listed.

The maximum damage to the semiconductor components, especially the solar cells, occur at much stronger inner belt. Severe weight penalties are incurred if sufficient shielding is to be provided for this zone. Hence, the inner belt is avoided altogether for satellite orbits. That limits the LEO altitudes from 500 km to about 1,500 km. The other re-

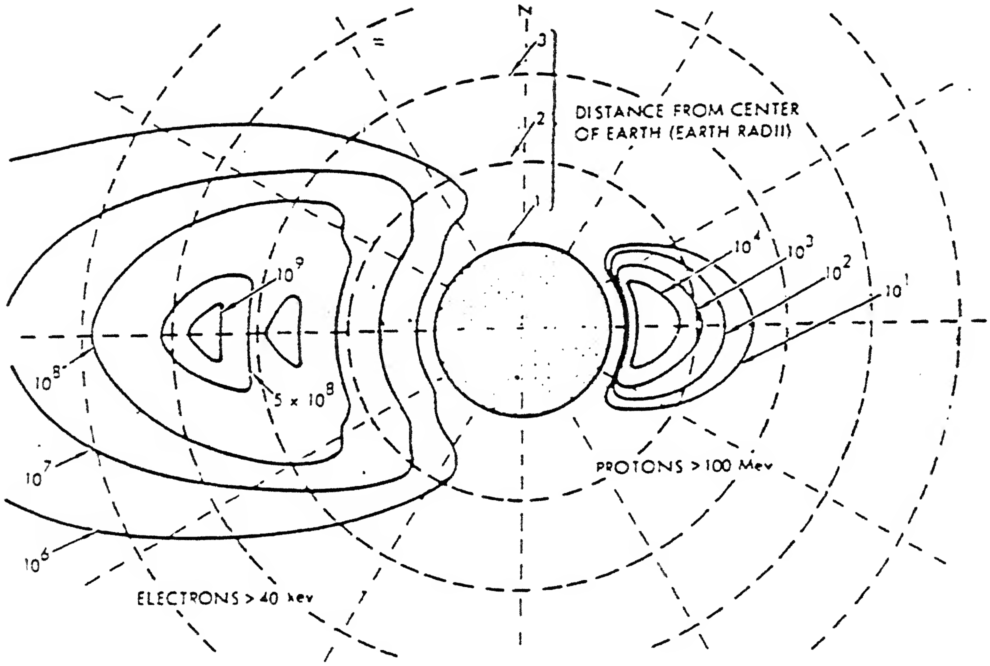

Figure 2.5: Spatial extent of trapped radiation belts in planes normal to the solar wind [14].

Table 2.4: Particle energy and intensity in the Van Allen belts [11].

Location	Particles	Energy	Intensity (particles/cm^2-sec)
Heart of inner belt (~ 3,600 km)	Electrons	>20 keV	3×10^{10}
		>100 keV	10^{10}
		>600 keV	10^{8}
		>1 MeV	10^{5}
	Protons	>10 MeV	10^{5}
		>40 MeV	2×10^{4}
		>650 MeV	10^{2}
Heart of outer belt (~ 16,000 km)	Electrons	>20 keV	10^{11}
		>200 keV	$\leq 10^{8}$
		>1.5 MeV	10^{4}
	Protons	>60 MeV	10^{2}
		<30 MeV	1

Table 2.5: Radiation damage thresholds of certain classes of materials [14].

S.No.	Class of components	Threshold of radiation limits
1	Electronic components	10^{1}-10^{3} rad
2	Polymeric materials	10^{7}-10^{9} rad
3	Lubricants,hydraulic fluids	10^{5}-10^{7} rad
4	Ceramic, glasses	10^{6}-10^{8} rad
5	Structural metals, alloys	10^{9}-10^{11} rad

gions available for use are the zones between the two belts, i.e altitudes in the vicinity of about 10,000 km (ICO) and the region above 20,000 km altitude with reasonable amount of protection. Moreover, the decreasing intensity of the belt on either side of the geomagnetic equator (completely vanishing beyond $\pm 45^o$ latitude) implies the existence of a rather large useful range of orbital inclinations with associated daily energy dose lying well within safe limits of exposure with minimal shielding.

2.7 Conclusion

From the previous description we can come to the following conclusions.

(a) The relative periods of visibility for a satellite from a ground station rapidly increases with increase in altitude.

(b) The orbital altitudes are governed by the communication power requirements. The presence of radiation belts severely limits the available orbit options.

(c) The launch power requirements continually increase with the orbital altitude as well as change in inclination required to achieve the final orbit. This may also be influenced by the relative position of the satellite with respect to the ground station during periods of visibility.

(d) The tracking requirements become more complex in lower orbits which involve a much larger number of fast moving satellites with respect to the ground stations.

(e) The satellites in LEO constellations have only a limited life-span. So, their periodic replacement by new ones is essential. It is therefore imperative that the satellites becoming non-functional are eliminated from the vicinity of the satellites still in use as new ones get added to replace them. It may not be too long before an international law on outer space may bind the owner nations to ensure proper procedures for disposal of "dead" satellites.

Chapter 3

Non-Geostationary Constellations For Global Coverage

3.1 Introduction

The most fascinating development in satellite communications has been the renaissance of interest in the non-geostationary orbits for personal communication via satellite. By the end of this decade it may be possible for a person to place a telephone call with a hand held unit the size of a pocket calculator from anywhere in the world to someone with a similar device anywhere else in the world.

Several projects using LEO and ICO satellite constellations are currently under study and development. Table 3.1 [2] sketches the orbital characteristics of some of the systems which are under development for providing 24-hr global coverage for personal communication. Apart from these there are many small-satellite systems under development as well as in use which do not provide real-time service. These systems are inherently suited for specific missions where limited data rates are required to be handled. Such satellites only fly across the service area for some tens of minutes and a few times a day. Examples are STARSYS (1300 km altitude, 24 satellites), TEMISAT (950 km altitude, 2 satellites) and LEOSAT (970 km altitude, 18 satellites). All the systems described above come under the small-satellites category with weights varying from 50 kg to 1,000 kg. This can be compared with the increasing masses at launch of the INTELSAT geostationary satellite

Table 3.1: Orbital parameters for some NGSO constellations providing global coverage [2]

System	Type/ Altitude	Inclination (degrees)	Period (minutes)	Orbital planes	Satellites per plane	Total satellites
ARIES	Circular/ 1018 km	90	206	4	12	48
CALLING	Circular/ 700 km	98.2	99	21	40	840
ELLIPSO BOREALIS	Elliptic/ 520 - 7800 km	116.5	180	3	5	15
ELLIPSO CONCORDIA	Circular/ 7800 km	0	280	1	9	9
GLOBALSTAR	Circular/ 1389 km	47 52	114	8 8	3 6	24 48
IRIDIUM	Circular/ 780 km	86.4	100	6	11	66
ODYSSEY	circular/ 10373 km	55	360	3	4	12

series, which culminates at 4400 kg with the INTELSAT-7A satellite.

In this chapter an analysis is made of the geometry of some NGSO constellations that can provide global coverage, with special emphasis on LEO constellations.

In designing a constellation for optimized worldwide coverage, the first step is to choose a set of common-altitude orbits which minimize the maximum great circle range ψ, considering all possible observation points on Earth at all possible instants of time. The constellation altitude is then chosen to obtain a guaranteed minimum elevation angle sufficiently high (10^o in our study) so that atmospheric propagation anomalies or local terrain obstructions are not a significant problem. All satellite orbits are assumed to be circular because the goal of worldwide visibility implies that no particular part of the Earth should be favored over another. For the same reason, all orbits are assumed to have the same altitude h and period T. An analysis of orbital perturbations (i.e. non-zero eccentricities or long term drift in orbital constants) has not been taken up here. These perturbations can be minimized by periodic station-keeping corrections, but would probably require one to choose a slightly overdesigned constellation to begin with to allow for possible degradation.

3.2 Types of Constellations

Based on their geometry, the satellite constellations can be divided mainly into two types—polar and non-polar. These can be further subdivided into symmetric and non-symmetric.

In the polar constellations, the orbital planes have a common intersection at the poles. The plane separation and satellite spacing are adjusted to minimize the total number of satellites required. In the symmetric polar orbits equal spacing between all the adjacent orbits result in an unnecessarily large overlap between satllites in adjacent orbital chains which move in the same direction [6]. The non-polar constellations may consist of random orbits or symmetric inclined orbits with equal inter-orbit angular spacing and intersatellite phasing governed by a prespecified rule.

In our study we have taken up the case of polar non-symmetric constellations based on the work done by Beste [6] and non-polar symmetric constellations based on workdone by Ballard [7]. A comparative study of the two has been carried out to highlight the differences.

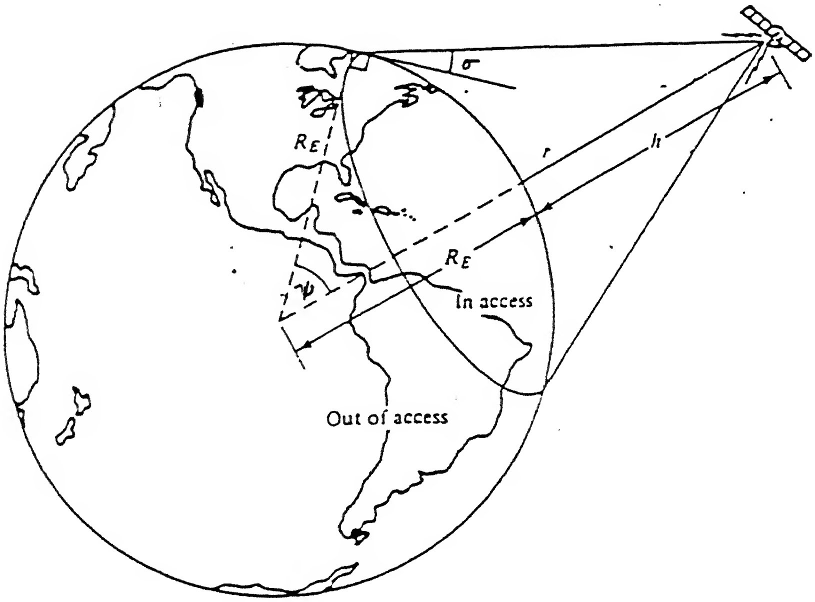

Figure 3.1: Earth coverage of a satellite at altitude h

3.3 Geometry of Polar Non-Symmetric Constellations

The most crucial parameter which determines the necessary number of satellites and orbits is the orbit height. This forms the starting point of our analysis.

The *footprint* is that part of the surface of the Earth where the satellite can be seen under the range of elevation angles above σ_m (Fig. 3.1 [5]). Thus, the footprint is a spherical segment of the Earth with the central angle ψ given by

$$\psi = \frac{\pi}{2} - \sigma_m - \arcsin\left(\frac{R_E}{R_E + h}\cos\sigma_m\right) \tag{3.1}$$

The angle ψ is the Earth-centred half cone angle corresponding to the coverage of one satellite, or equivalently, it is also referred to as the radius of the coverage circle on the surface of the Earth. The surface area on the Earth covered by the satellite is given by [5]

$$S = 2\pi R_E^2 (1 - \cos\psi) \tag{3.2}$$

Satellites in adjacent orbital planes move in the same direction, and the satellites of one

plane are shifted relative to each other by one half of the intraorbit spacing (i.e. π/q, where q is the number of satellites per orbit). This configuration (Fig. 3.2) clusters the satellites in an optimal manner at the equator. At the two boundaries where the two orbital chains move in the same directions, the relative geometry is not constant, so that the angular separation between orbital planes must be smaller than the angular separation between orbital planes of satellites moving in the same direction. The most demanding requirement on ψ occurs at the equator, where the following equation must be satisfied [6]:

$$(p - 1)\,\psi + (p + 1)\,\Delta = \pi \tag{3.3}$$

where,

$$\begin{aligned} p &= \text{the number of orbital planes} \\ \Delta &= \cos^{-1}\left[\frac{\cos\psi}{\cos(\pi/p)}\right] \end{aligned}$$

The p orbital planes are separated in angle by Γ where

$$\Gamma = \psi + \Delta \tag{3.4}$$

This results in an angular plane separation of 2Δ at the boundaries where satellites in adjacent orbital planes move in opposite directions. The above equations are valid for single coverage only, i.e. at least one satellite is always visible at any given time at any point on the Earth.

Eqn. 3.2 was evaluated for a wide range of combinations of p orbital planes and q satellites per orbital plane. The results are summarised in Table 3.2, which also shows the orbital plane separation Γ and orbital altitude h. The last column represents the ratio of the total solid angle covered by all the satellites to 4π sr. It is seen that in almost all the cases the ratio is nearly equal to 2. The implication is that the coverage averaged over the entire sphere is double. Ideally, this value should be unity if all the satellites were to be held stationary in space and spaced optimally. The higher values of coverage ratio achieved reflect the extent of overlap between satellite footprints at higher latitude regions with optimum phasing ensured at the equator. The results obtained here represent a generalization of the earlier study of Beste.

Table 3.2 can be used to select the most optimum constellation for a specified altitude. For example, if we want to select a constellation for 1000 km altitude we have two options–

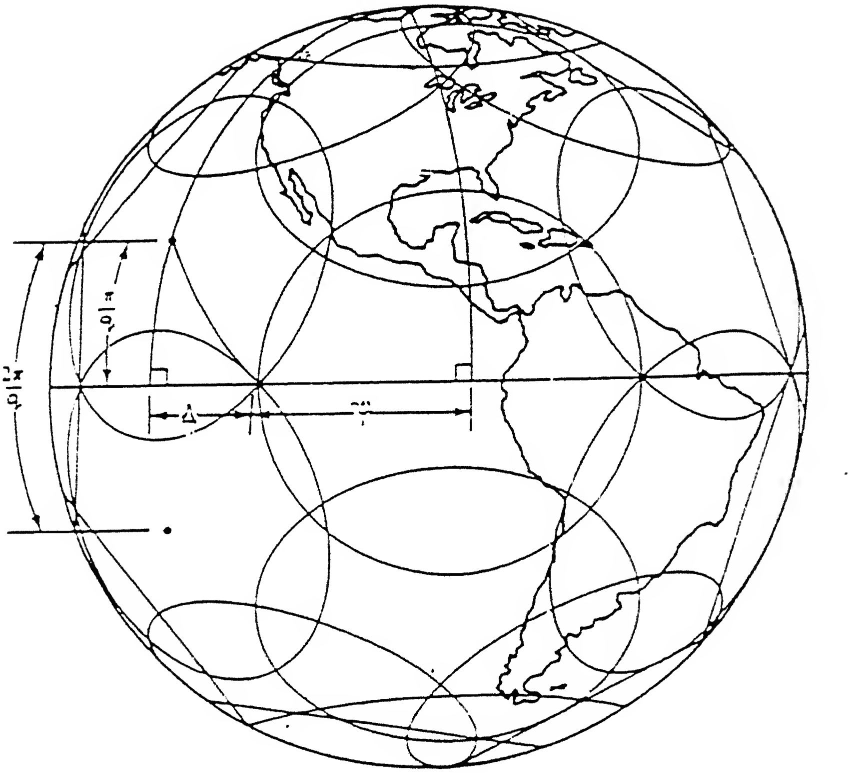

Figure 3.2: Polar orbit geometry for continuous single visibility coverage with optimum phasing [5].

Table 3.2: Best single visibility polar constellations for different N

Number of satellites	Number of planes	Satellites per plane	ψ (deg.)	Γ (deg.)	Altitude (km)	Coverage ratio
6	2	3	65.97	103.98	19524.83	1.78
8	2	4	57.26	98.17	9870.00	1.84
10	2	5	52.87	95.24	7393.82	1.98
12	2	6	50.61	93.74	6421.54	2.19
12	3	4	48.53	69.27	5654.79	2.03
15	3	5	42.20	66.10	3868.93	1.94
18	3	6	38.62	64.31	3124.34	1.97
21	3	7	36.26	63.13	2707.46	2.03
24	3	8	34.91	62.45	2490.76	2.16
20	4	5	37.64	51.06	2943.76	2.08
24	4	6	33.51	49.40	2282.42	1.99
28	4	7	30.68	48.27	1904.43	1.96
32	4	8	28.68	47.47	1667.58	1.96
36	4	9	27.38	46.95	1526.32	2.02
40	4	10	26.57	46.63	1442.79	2.11
30	5	6	30.94	40.31	1936.75	2.13
35	5	7	27.73	39.24	1563.22	2.01
40	5	8	25.55	38.52	1341.96	1.96
45	5	9	24.13	38.07	1209.93	1.97
50	5	10	22.91	37.64	1103.96	1.97
55	5	11	22.04	37.35	1031.60	2.01
36	6	6	29.75	34.21	1791.31	2.37
42	6	7	26.05	33.16	1390.55	2.13
48	6	8	23.99	32.57	1197.60	2.07
54	6	9	21.90	31.97	1020.38	1.95
60	6	10	20.88	31.68	940.33	1.97
66	6	11	19.77	31.36	857.77	1.94
72	6	12	19.02	31.15	805.22	1.97

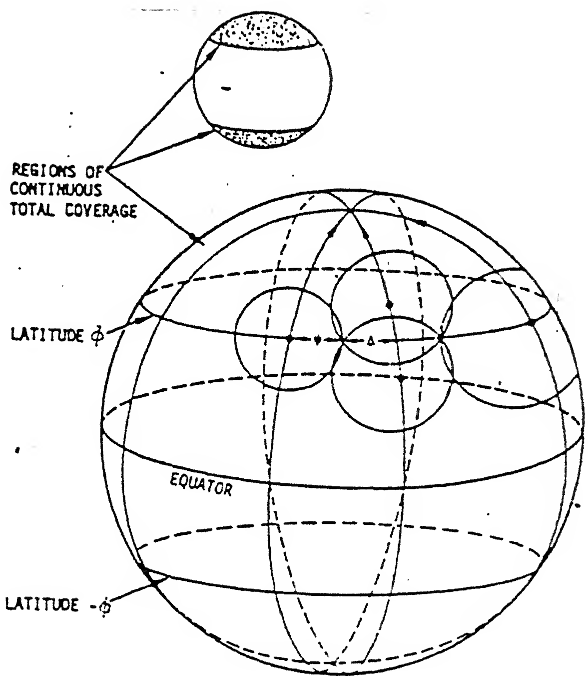

Figure 3.3: Coverage geometry at latitude ϕ [6].

the 5×11 constellation at 1032 km altitude or the 6×9 constellation at 1020km altitude. The 6×9 constellation appears to be a better choice because of the lesser number of satellites and smaller coverage ratio. Similarly, if we deploy a 36 satellite constellation the 4×9 geometry gives h=1526 km and coverage ratio of 2.02 as compared to the 6×6 geometry which gives h=1791 km and a coverage ratio of 2.37.

3.3.1 A scheme for partial global coverage with full coverage in higher latitude regions

The preceding analysis can be extended to coverage in high latitude regions i.e. latitude, say, $+\phi$ and the north pole, as well as between the latitude $-\phi$ and the south pole. Fig. 3.3 shows the geometry. Here, the optimal coverage must be achieved at ϕ degrees rather than at the equator. In this case, the requirement on angular spacing gets modified to:

$$(p - 1)\,\psi + (p + 1)\,\Delta = \pi \cos \phi \tag{3.5}$$

Such types of constellations can be used to provide coverage specifically for the polar regions which cannot be accessed by the geostationary satellites. Table 3.3 summarizes

Table 3.3: Spacing requirements for single coverage of polar regions beyond latitude ϕ

Latitude ϕ(deg)	No. of planes, p	satellites/ orbit, q	ψ (deg)	Γ (deg)	Altitude h (km)	Coverage ratio
	2	4	53.4	103.1	7926	1.65
30	3	7	33.3	64.5	2266	1.73
	4	9	25.3	47.8	1319	1.73
	2	4	49.6	111.2	6311	1.45
45	3	7	30.0	66.9	1819	1.41
	4	9	22.75	49.2	1090.55	1.42
	3	8	24.57	49.15	1250	1.09
60	4	4	24.36	48.72	1230	0.71
	4	9	20.28	40.56	895	1.12
	3	4	16.52	36.56	641	0.25
75	3	7	18.59	38.45	775	.55
	4	4	9.89	51.27	301	.12

the results developed using the above equation.

3.4 Non-Polar Constellations

One major drawback of the polar orbits is that they result in higher satellite densities at the poles than at the equator. It seems intuitive that the orbital configuration which results in a more uniform distribution of satellites over the Earth would lead to a more efficient coverage. Ballard [7] has suggested some special constellations having rosette orbital patterns (flower-like) which exibit very good worldwide coverage properties. The coverage properties of these constellations are analysed in terms of the largest possible great circle range between an observer anywhere on the Earth's surface and the nearest subsatellite point. When evaluated in this manner, the coverage properties are invariant with deployment.

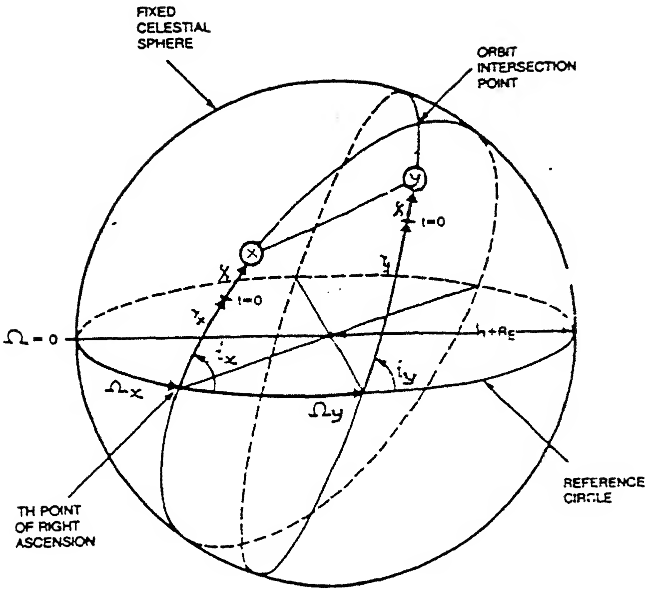

Figure 3.4: Geometry of satellite pair [7].

3.4.1 Basic geometry of rosette constellation

The class of constellations described here is characterised by circular orbits having the same period and same inclination with respect to an arbitrary reference plane. The orbits are uniformly distributed in right ascension. Furthermore. the initial phase position angle of satellites increases in proportion to the right ascension angle. The name "rosette" has been chosen because the pattern of orbital traces. when drawn on a fixed celestial sphere. resembles a many petalled flower.

Fig. 3.4 illustrates the basic parameters needed to describe the position of typical satellites in a constellation. All satellites move in circular paths on the surface of radius R_E+h. The position of any satellite on this fixed celestial sphere is described by three constant orientation angles, along with a time-varying phase angle.

Ω_x = right ascension angle for the xth orbital plane.

i_x = inclination for the xth orbital plane.

γ_x = initial phase angle for the xth satellite in its orbit plane at t = 0, measured from the point of

right ascension.

$$\chi \;=\; 2\pi\,\mathrm{t}/\mathrm{T} \;=\; \text{time varying phase angle for all satellites of the constellation.}$$

In a rosette constellation having p planes and q satellites per orbit, the orientation angles have the symmetrical form

$$\begin{aligned} \Omega_x &= 2\pi x/p, \;\; x = 0 \; to \; N - 1 \\ i_x &= i \qquad \text{for all x} \\ \gamma_x &= m\Omega_x = m\,q\,(2\,\pi\,x/N) \\ & \quad m = (0 \text{ to } \mathrm{N}-1)/q \\ & \quad \mathrm{N} = p\,q \end{aligned} \tag{3.6}$$

The harmonic factor m is an important descriptor of the rosette constellation. It influences not only the initial distribution of the satellites over the sphere, but also the rate at which the constellation pattern precesses around the sphere. As m takes on different values, different constellation patterns are generated. If m is a simple integer, a constellation having one satellite in each of the N planes (N=p) is being referred to. However, different integer values of m may lead to different constellation patterns with different coverage properties. The intersatellite great circle range r_{xy} between any arbitrary pair of satellites in a constellation is illustrated in Fig. 3.4. Using the half angle formulas from spherical trigonometry, and applying the special conditions of Eqns. 3.6, the intersatellite range in a rosette constellation can be expressed in the form [7]

$$\begin{aligned} \sin^2(\frac{r_{xy}}{2}) \;=\; & \cos^4(\frac{i}{2})\, sin^2[(m+1)(y-x)(\frac{\pi}{p})] \\ & +2\,\sin^2(\frac{i}{2})\,\cos^2(\frac{i}{2})\,\sin^2[m(y-x)(\frac{\pi}{p}) \\ & +\sin^4(\frac{i}{2})\,\sin^2[(m-1)(y-x)(\frac{\pi}{p}) \\ & +2\,\sin^2(\frac{i}{2})\,\cos^2(\frac{i}{2})\,\sin^2[(y-x)(\frac{\pi}{p}) \\ & \times \cos[2\,\chi + 2\,m\,(y+x)(\frac{\pi}{p})] \end{aligned} \tag{3.7}$$

Fig. 3.5 illustrates that the worst possible observation point in a spherical triangle formed by joining three subsatellite points (x,y,z) is at the orthocentre of the triangle, henceforth

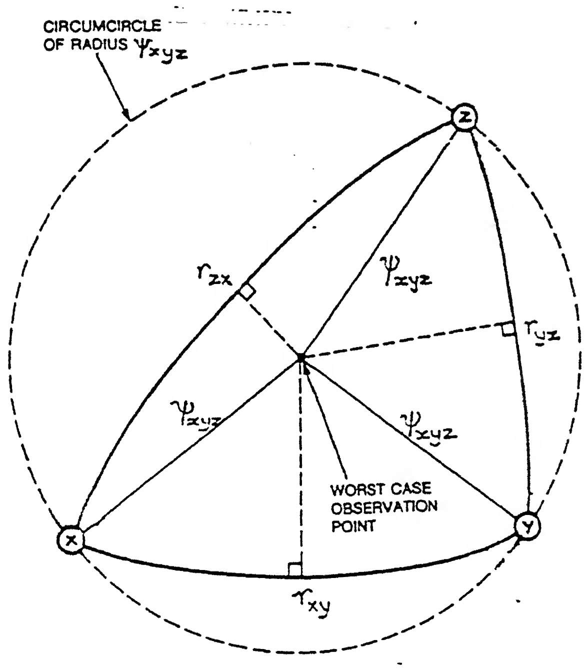

Figure 3.5: Equidistance of satellite triads [7].

referred to as the midpoint of the triangle. The range arc from the midpoint of the triangle to any of the three vertices is the equidistance ψ_{xyz}. A constellation providing usable coverage only to a range, say, $\psi_o < \psi_{xyz}$ leaves the midpoint uncovered and therefore fails the test of global coverage. If ψ_o becomes equal to ψ_{xyz}, or if it exceeds this value the number of satellites visible at the midpoint changes from zero to three, and at least single visibility is assured everywhere within the triangle. Knowing the three sides of the spherical triangle, its equidistance parameters can be computed from the formula [7]

$$\sin^2 \psi_{xyz} = \frac{4ABC}{(A+B+C)^2 + 2(A^2 + B^2 + C^2)} \tag{3.8}$$

where,

$$A = \sin^2(\frac{r_{xy}}{2})$$

$$B = \sin^2(\frac{r_{yz}}{2})$$

$$C = \sin^2(\frac{r_{zx}}{2})$$

The coverage properties of a constellation can therefore be analysed by examining the equidistances $\psi_{xyz}(\chi)$ of its spherical triangles at all instants of time to find the worst case

of coverage. With a constelletion using, say, N satellites, a total of 2N - 4 nonoverlapping triangles are required to cover the sphere, and all must be examined for the worst case equidistance. The worst case observer on the Earth's surface will be one whose position coincides with the midpoint of the spherical triangle having the largest equidistance. In dividing the sphere into triangles, care must be taken to choose only those triangles whose circumcircles (fig. 3.5) enclose no other satellites. Once another satellite moves inside the circumcircle of the triangle, that triangle is no longer of interest in a single visibility analysis because a set of smaller triangles can then be chosen whose circumcrcles are all empty. Using these methods, the best single visibility rosette constellations for N = 5 to 15 have been obtained by Ballard [7]. For the sake of comparison an analysis of constellations with N = 36 (9 orbits $\times$ 4 satellites per orbit) was also undertaken. All the results are summarized in Table 3.4. For each value of N, the table shows the number of planes p, the harmonic factor m, and the orbit inclination i which produce the smallest minimax range ψ. The replication phase interval is also shown for each constellation, along with the lowest altitude h (in earth radius units) and corresponding orbit period T (in sidereal hours) for a guaranteed 10^o minimum elevation angle. On comparing the results of Table 3.2 with Table 3.4 it is seen that

(a) minimum number of satellites required for 24-hours global coverage with polar orbits is six whereas the same coverage can be provided by five satellites in rossete constellation.

(b) the rosette constellations show better results than polar constellation for N = 5 to 15. However, it is seen that the altitudes corresponding to N = 11 to 15 lie within the inner zone of the Van Allen belts with N = 15 lying at the heart of the inner belt. Hence, these constellations cannot be used without adequate shielding. A case study was taken up for rosette constellations at low earth orbits. For this a constellation of 36 satellites was chosen in two different geometries (9$\times$4). The results show that the optimum inclination has gone higher for global coverage owing to smaller minimax range. The minimax range was also found to be higher as compared to that of a 36 satellite polar constellation. An analysis was also carried for the 9$\times$4 constellation for global coverage excluding the polar regions. In this case the results were more comparable to the polar constellation with the advantage of a more uniform distribution of satellites. It may be noted here that the 36 satellite constellations taken

Table 3.4: Best single visibility rosettes for global coverage for N = 5 to 15 [7]and results obtained from present study for N = 36.

constellation dimensions			replication phase interval (deg)	Optimum inclination i (deg)	Minimax range ψ (deg)	Lowest deployment for elevation$\geq 10^o$	
N	p	m				h (e.r.u)	T (hours)
5	5	1	36	43.66	69.15	4.232	16.90
6	6	4	60	53.13	66.42	3.194	12.13
7	7	5	25.7	55.69	60.26	1.916	7.03
8	8	6	90	61.86	56.52	1.472	5.49
9	9	7	20	70.54	54.81	1.314	4.97
10	10	7	36	47.93	51.53	1.066	4.19
11	11	4	16.4	53.79	47.61	0.838	3.52
12	3	$\frac{1}{4},\frac{7}{4}$	30	50.73	47.90	0.853	3.56
13	13	5	13.8	58.44	43.76	0.666	3.04
14	7	$\frac{11}{2}$	25.7	53.98	41.96	0.598	2.85
15	3	$\frac{1}{5},\frac{4}{5}$	12	53.51	42.13	0.604	2.87
36	9	$\frac{1}{4}$	10	69.0 (global coverage)	34.5	0.38	2.28
36	9	$\frac{1}{4}$	10	41.2 (excluding polar regions)	28.9	0.303	2.09

up in this study may not provide the best single visibility coverage. This is due to the fact that various geometries may be obtained by changing the value of the harmonic factor m and each such constellation has one best condition of satellite triads. Due to pausity of time only a few particular values of m could be considered and the configurations leading to the best results were selected . However, there exists possibilities for improving minimax range further for other values of m which could not be examined.

3.4.2 Mixed orbit constellations

A combination of different types of orbits can also be used to advantage for a global coverage. Some of the feasible combinations are as follows:

(a) Inclined orbit constellations not covering the polar regions: This will permit a lower orbital height. Since the traffic density at the polar regions is much lower and mainly for scientific and positioning information. a separate polar orbit can be added to cover specifically the polar regions. The number of satellites in this orbit can be decided as per the traffic requirements.

(b) Three mutually orthogonal orbital planes: The interorbit relative phase can be adjusted while maintaining the intraorbit spacing of 90^o so as to minimize the maximum distance from a satellite to a point in any quadrant. For the case of q=3. in a configuration of 12 satellites, the resulting coverage angle is $\psi = 50.8^o$ [6] which compares favourably with a coverage of 48.6^o provided for 12 satellites in polar orbits.

3.5 Quasi-Stationary Deployments

So far, the Earth's rotation inside the celestial sphere of the constellation has been totally ignored. This makes no difference if the nondiscriminating world wide coverage is adopted as a goal. The only effect of the rotating Earth is to cause the worst case observation point to undergo continual shift on the Earth's surface. However, sometimes it may be desirable to provide continuous coverage only over a particular zone of interest. Quasi-stationary orbit systems provide an answer to this problem. As explained in chapter 1.

the satellite deployments which cause the subsatellite points of a constellation to follow a fixed ground track patterns on the Earth's surface are known as " quasi-stationary". Use of this type of constellations results in much simpler antenna beam steering design. The rosette constellation can be made use of in design of the QSO constellations for providing global coverage as shown by Ballard [7]. Here, it is proposed to take up the case of 24-hour QSO satellites to provide zonal coverage with an aim to supplement the capacity of the geostationary satellites.

3.5.1 24-hour quasi-stationary orbit for zonal coverage

Till now, we have considered cases only for continuous global coverage through a satellite constellation. Since we are looking for alternatives to GSS due to the excess future communications demand and limited geostationary arc, it may appear desirable to enhance its capacity. A rather simple approach to achieve this objective is by utilizing the 24-hour QSO satellites along with the GSS to share the communications load of a particular region. By proper selection of orbital parameters and number of satellites a constellation can be designed to ensure continual coverage of the region of interest. The orbits can be either elliptic or circular depending on the nature of communications load requirement. The ground track equations in terms of Earth latitude (ϕ) and longitude (λ) coordinates for an orbit can be given by the equations [7]

$$\sin\phi = \sin i \, \sin(\omega + \nu) \tag{3.9}$$

$$\tan(\lambda_o + \omega_e t - \Omega) = \cos i \, \tan(\omega + \nu) \tag{3.10}$$

The value of true anamoly ν for an orbit at any instant can be found from the equations [15]

$$\begin{aligned} M &= n_s(t - t_e) \\ M &= E - e \sin E \\ \tan(\frac{\nu}{2}) &= \sqrt{\frac{1+e}{1-e}} \tan(\frac{E}{2}) \end{aligned}$$

where, n_s = mean angular speed of the satellite. Fig. 3.6 shows the ground track of a 24-hour QSO satellite for different values of inclination, argument of perigee, right ascension and eccentricity. It is evident from the figures that if the values of orbital parameters

Satellite	Inclination	Right Ascension	Argument of Perigee	Eccentricity
a	12^o	160^o	-90^o	0
b	12^o	160^o	-90^o	0.1
c	12^o	160^o	-90^o	0.2
d	12^o	160^o	-75^o	0.1

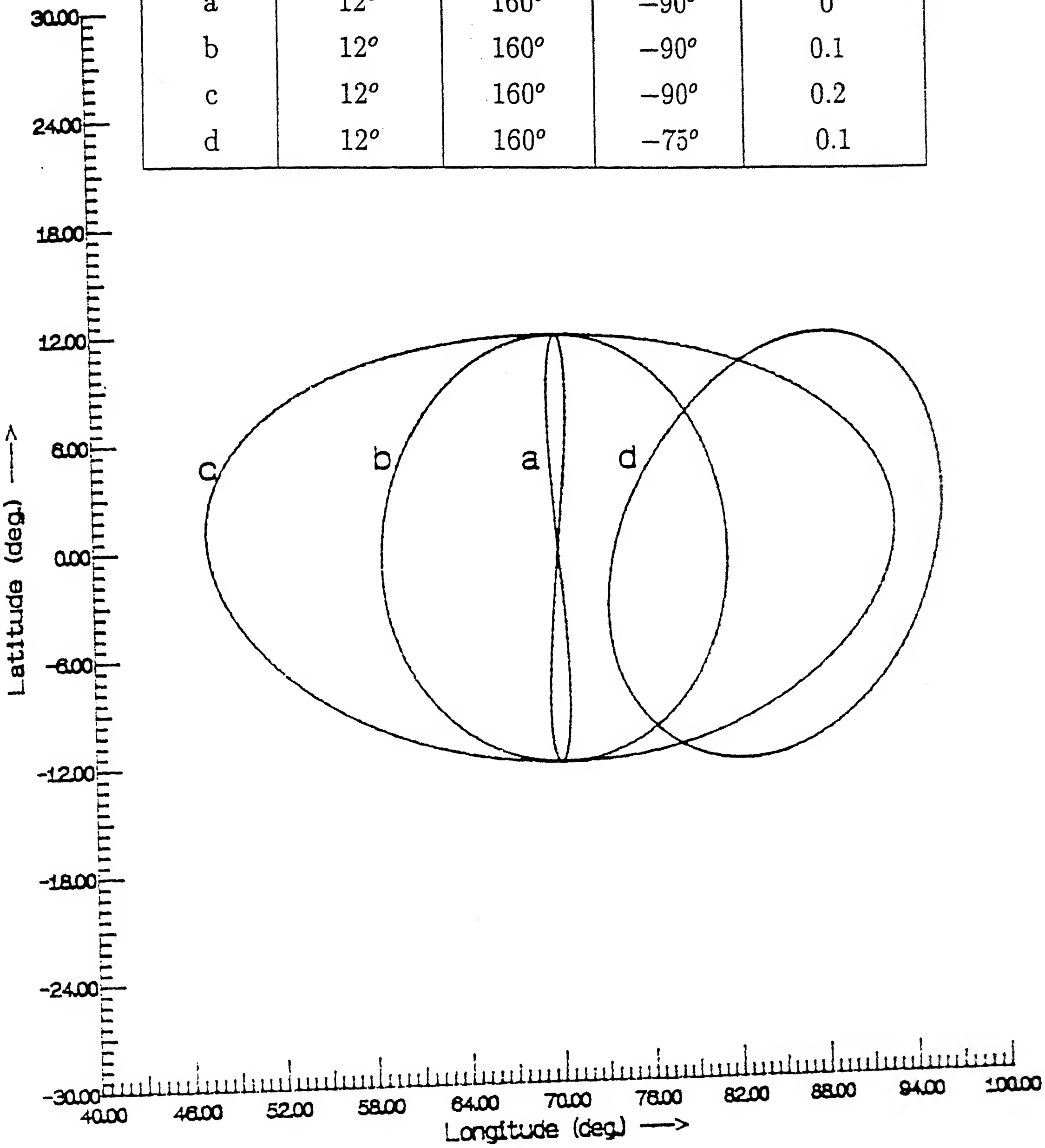

Figure 3.6: Ground tracks of 24-hour QSOs with different orbital parameters

are chosen properly, the satellite can be used to provide continuous zonal coverage, e.g. as in case 'd', in the area of interest, thereby providing supplementary communications capacity. Also, more than one satellite can coexist in the same zone provided the condition of minimum angular separation is maintained to avoid interference. If three satellites could be put into such orbits so that they are simultaneously visible from any point in the zone, then they could be used for the purpose of position determination similar to the GPS systems. Four such satellites would provide altitude information also. The main advantage of such a system is that it can be effectively utilized for multiple purposes, including communications, navigation, scientific and meteorological applications. The disadvantage of using elliptical orbits is the continuous variation in altitude which means variation in transmitted power. The difference between apogee and perigee distance for a 24-hour elliptic orbit with e=0.1 is nearly 8,400 km and for e=0.05 it is nearly 4,200 km. For higher eccentricities, these values become proportionately higher. However, this problem can be overcome by the use of variable gain transmitters whose gain may be made to vary as square of distance and hence a predetermined function of time.

Chapter 4

Networking Aspects in a Non-Geostationary Satellite Based System

The need for communication and its global distribution. as well as the kind and quality of services to be offered, add up to a number of requirements (e.g. upper limits for the delay in voice services) in a user-oriented system design at the lowest possible costs. With respect to this task. the main system parameters are the number of communication satellites. gateway earth stations (network nodes), and the number and kind of communication links in the network.

A high degree of connectivity within an LEO/ICO satellite network can be achieved by a sufficient number of such network nodes and corresponding links between them. The higher the degree of connectivity, the more the alternatives for routing become available. and therefore a good traffic flow distribution is possible. Moreover, it enhances the flexibility of the network to cope with the link or node failures. On the other hand. the construction and positioning of more gateways (also referred to as hub stations) and/or satellites means higher fixed costs, while permanent demand of large capacities implies higher recurring costs.

The various types of links which may be used in a network (Fig. 4.1)can be described as follows [3,4].

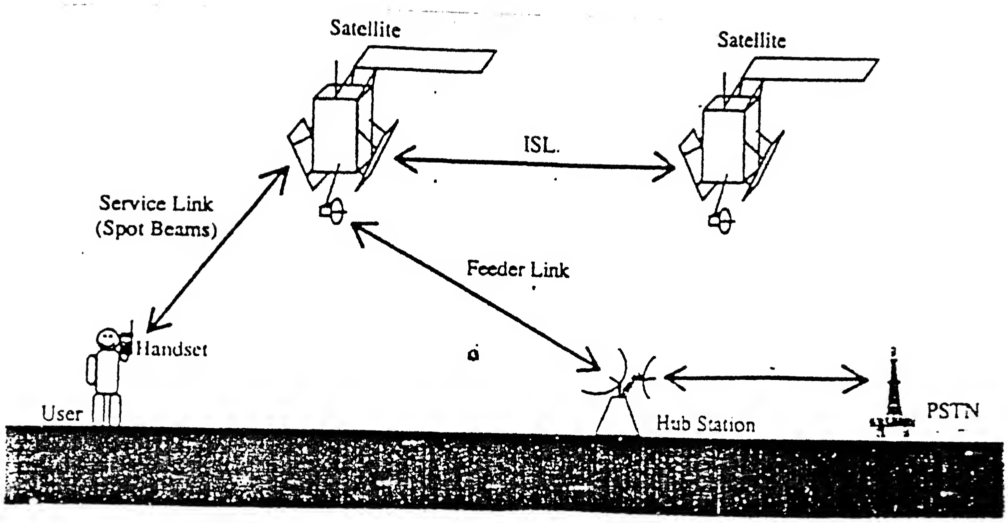

Figure 4.1: System elements in an NGSO satellite network [3].

(a) Mobile User Link (MUL) or Service Link : Links between satellites and those mobile users within their footprint, who communicate via the satellite.

(b) Gateway Links (GWL) or Feeder Links : Links between satellites and gateways or hubstations in the coverage area of the satellites.

(c) Links through PSTN/PDNs (Public Switched Telephone Networks / Public Data Networks) : These refer to the totality of the existing telephone and data networks. and can cater to communications among all fixed users and mobile LEO / ICO system users via gateway stations.

(d) Intersatellite Links (ISL) : Direct satellite-satellite connections. the ISLs may connect satellites within the same orbit (intra-plane) or satellites in adjacent orbits (inter-plane). These are useful in transporting the traffic as far as possible through the space segment, thereby, minimizing the number of gateway stations. Theoretically, one gateway station could be sufficient for global connectivity. If the system does not provide ISLs, then the whole long distance traffic has to be transported through public lines. In this case, it is necessary for global connectivity that every satellite has connection to at least one gateway station at any instant of time.

The basic criterion for selection of right links to route a call is to have the minimum

possible propagation delay along with cost-effectiveness. Discussed below are some more important parameters in the networking of a system [4].

(a) The division of footprints into spotbeams : By the use of multibeam antennas, the footprints can be divided into small cells (Fig. 4.2). Typical number of spot cells are $N_z = 3$, 4, 7 or 9 [15]. Another advantage is the reduction of RF power for MULs due to the concentration of power over smaller areas.

(b) Required frequency bands (MULs in L-band or S-band and GWLs in C-band, Ku-band and Ka-band) : The transmission power increases with increasing frequencies. On the other hand, higher frequencies are better available and the co-ordination of the coexistence of different systems becomes easier at higher frequencies.

(c) Multiple access protocols for uplinks: The selected multiple access protocol influences the required bandwidth for the whole system. This aspect lets Time Division Multiple Access (TDMA) techniques appear as appropriate candidates. But spread spectrum or code division multiple access (SSMA/CDMA) techniques make the co-ordination of different systems easier.

In the following sections we discuss the various problems faced in NGSO satellite based systems and how these are overcome.

4.1 Intersatellite Interference

Before any new system can be constructed, it is necessary to demonstrate that it can be co-ordinated with existing systems and will not present any unacceptable level of interference. A detailed interference analysis of the system is therefore necessary. The significant difference between an NGSO system and the typical GSO system is that, unlike the case of geostationary orbits, the relative geometry between a satellite and an earth station or among the satellites themselves is not fixed. This time-dependent geometry significantly enhances the complexity of the calculations.

The carrier signal from each interfering satellite can be considered to represent noise to the interfered-with system. The noise contribution due to all the visible interfering satellites represents the total noise. It may be pointed out that the gain of an antenna is a function of its direction of transmission or reception of the signal with reference to its

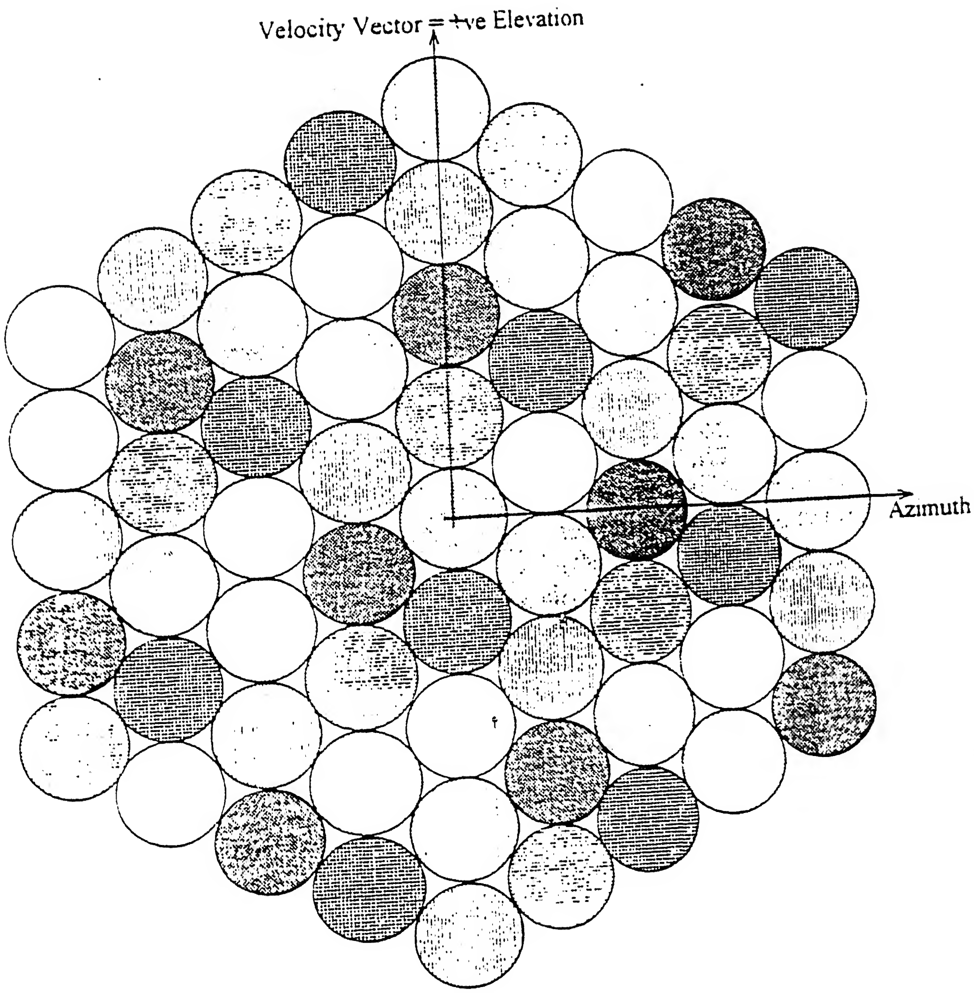

Figure 4.2: Spot beam pattern showing frequency reuse [3].

rincipal axis. Due to the constantly changing geometry of the constellation the noise level ɔ a satellite also keeps varying with time and it must be ensured that the interference ɜvel remains below acceptable limits in accordance with international Radio Regulations ike RR 2613 which requires an NGSO satellite to cease emission whenever interference vith the GSO system is unacceptable.

4.2 Handover Procedures

In a satellite system based on NGSO constellation the network has to cope with the motion of satellites as well as that of terminals. This has an impact on the procedures for local-registration and handover [2]. Handover may be defined as the procedure performed in case it is necessary to change the radio communication path during a communication transaction in order to maintain service quality. In addition, handover may also be needed in order to free the network resources in areas with high traffic load.

Local-registration can be defined as the procedure that allows the terminal to provide the network with the information necessary to correctly route the mobile-terminated calls. In an NGSO satellite-based system, this information can be based on terminal location data (e.g. latitude and longitude). In this way, since the orbital parameters are known, it is always possible to identify the proper satellite and spot-beam through which the calls can be routed.

In a satellite system based on NGSO orbits, the traffic handover occurs mainly owing to the motion of the antenna footprints of the various satellites belonging to the constellation. In general, the handover may be of two types : a link may be switched between two spot-beams of the same satellite or between two spot beams of two different satellites. In case of a mobile link, both kinds of handovers may take place. But in the case of a fixed earth station, a multiple spot-beam antenna is generally not required for the feeder link. Hence, only handover between satellites may occur for the earth stations.

In particular, in the case of mobile handover between spot-beams of the same satellite, the current satellite remains in visibility of the terminal, but the communication needs to be supported by another spot-beam. In the case of mobile handover between satellites, the current satellite is moving out of visibility of the terminal. In this case, the communication is switched over to another satellite. Similarly, in the case of earth

;ion handover, the current satellite is moving out of visibility of the earth station. In ; case, communications are switched over to another earth station which is within the ·erage of the same satellite, or alternatively, in case of constellations having switching)abilities in the space segment (e.g. IRIDIUM) the communications are handed over a new satellite in visibility of the same earth station.

Even though the above mentioned handover modalities apply in a very general case, it not always necessary to implement each handover option, thus allowing a considerable aount of system complexity reduction, although at the expense of some limitations. For :ample, in the ODESSEY system, no handover is performed [2]. This approach does)t degrade the overall system performances since the ICO constelletion provides long .sibility periods for each satellite in the service area (almost 2 hours, each satellite being sed only during the intervals which provide the highest elevation angles). Therefore, nly a small percentage of calls (less than 5 percent of the overall traffic) is active during atellite change-overs. These are catered for by a sort of 'network' handover, i.e. the ommunications still pending at 'old' satellite coverage shut-down are re-established free- ›f-charge on the new satellite. In addition to that, the steering antenna capabilities of ,hese satellites precludes the need for spot-beam handovers. As a matter of fact, the ;pot-beam pattern on the the ground tends to remain relatively fixed since the antenna is continuously reoriented to maintain coverage to the assigned region.

4.3 Tracking Strategies

Several satellites may be visible at any particular time at any earth station, such as handset and hub-station location. The number of satellites depends on a number of factors including the latitude of the earth station, the number of satellites in the constellation. the inclination of the planes in the NGSO constellation. and the current configuration of the constellation. This diversity allows the handset and earth station to select which particular satellite to communicate with. In case of the service link, where there are multiple spot-beams, there is also the need to select which spot to use. This selection process is called 'tracking strategy' [3].

Inclusion of a tracking strategy has important consequences for the dynamics. This can be seen by consideration of the following arguement, concerning interference from a

hub-station into a geostationary satellite.

Interference can only occur when the hub-station is pointing towards the GSO, or to within a few degrees of it. Hence, in a satellite system consisting of NGSO constellation, depending on the latitude of the hub-station, suitable bias must be placed on the hub-station elevation angle such that it takes the highest values without pointing towards the GSO.

We have, thus, seen that a proper selection of accessing techniques, handover procedures and tracking strategy can ensure optimum utilisation of the network along with minimum interference to the GSO.

Chapter 5

Summary and Conclusions

An attempt has been made in this study to look at the various NGSO constellations as possible alternatives to the GSO and compare the merits and demerits of these systems. Based on this study, the following conclusions can be made:

(a) The most important factor which determines the visibility of a satellite from the ground station is its altitude. This in turn determines the communication power required, number of satellites in the constellation and launching requirements.

(b) The tracking procedures become more complex at lower altitudes where the number of satellites is higher.

(c) The radiation hazards associated with the Van Allen belts impose severe restrictions on the permissible zones of satellite deployment. In contrast, utilizing the prohibited zone for satellites may demand adequate shielding leading to significant mass penalty.

(d) Due to the heavy crowding foreseen due to the use of a large number of LEO/ICO constellations, suitable disposal procedures may have to be ensured for the "dead" satellites.

(e) Out of the various available constellations, the non-symmetric polar constellation and the symmetric inclined (rosette) constellations appear to be the most likely choices. Though the polar constellations are much simpler in geometry they result in a higher amount of overlap at the poles due to the crowding of satellites at the poles. As

compared to these, the rosette constellations have the advantage of a more uniform distribution.

(f) Attitude control plays an important role in ensuring pointing of the antenna beams aboard the non-geostationary satellites towards the ground station. The quasi-stationary orbit constellations follow fixed ground tracks and hence can lead to simpler beam steering mechanisms. The 24-hr QSO systems can coexist with the GSO systems by ensuring a minimum intersatellite separation, thereby supplementing the capacity of the geostationary satellites.

(g) The dynamic (NGSO) constellations introduce additional problems of station-keeping, cross-linking and channel allocation to the network control agency, and additional problems of beam/channel switching to the network user. However, solution of these problems is well within the ambit of the current technology, although at somewhat higher costs.

(h) Intersatellite interference acts as a major hurdle towards the use of a multiple number of constellations simultaneously along with the geostationary satellites. Use of spread-spectrum techniques using CDMA has helped in reducing the interference levels to a large extent. An efficient use and coordinated sharing of the allotted frequency spectrum between satellites and proper tracking strategies will lead to further reduction in the interference levels.

(i) Potential users at latitudes beyond $\pm 70^o$ are not well served by geostationary satellites. No service at all is feasible with GSS beyond $\pm 80^o$ latitude. However NGSO constellations with worldwide coverage can adequately service these zones above some guaranteed minimum elevation angles.

(j) It is more difficult to disable a dynamic constellation, either by electronic jamming or by physical attack than it is to disable a geostationary satellite. In case a few satellites of the constellation become non-functional, the crosslinks of the satellite network could be reconfigured and operation could continue at least in degraded mode.

5.1 Recommendations for Future Work

A combination of various alternative orbits may be considered to developed constellations ensuring more uniform worldwide coverage with lesser number of satellites.

In context of India, which has fully depended upon geostationary satellites so far, it may be worthwhile to look into alternative LEO/MEO configurations at low latitudes which could ensure 100 percent coverage over the Indian subcontinent while maximizing the use of their spare capacity in other zones.

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